

Open heavy-flavour and quarkonium production in Pb-Pb and p-Pb collisions measured by the ALICE detector at the LHC

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Open heavy-flavour and quarkonia measurements are important tools to study the hot and dense partonic medium formed in ultra-relativistic heavy-ion collisions. The modification of their production in those collisions, with respect to the pp and p-Pb ones, can help in the characterization of this medium. Quarkonia and open heavy-flavour production is measured in ALICE in the three different collision systems, at mid- and forward rapidity. A selection of those results recently obtained in Pb-Pb and p-Pb collisions by the ALICE Collaboration is presented.

1 Introduction

The Large Hadron Collider (LHC) allows the study of ultra-relativistic collisions of heavy-ions, in particular Pb-Pb and p-Pb collisions. The ALICE experiment¹ was built to study in detail these interactions involving ions, in order to characterize the deconfined, highly dense and hot state of nuclear matter, known as the Quark-Gluon Plasma (QGP).

Pairs of charm and anti-charm quarks can be produced in the scattering between two partons with very high momentum transferred. At the LHC energy, those pairs are produced mainly via gluon fusion at tree level process or via gluon splitting or flavour excitation at higher order processes². Charm quarks that hadronise with light quarks form open heavy-flavour hadrons; in case heavy quarks pair among themselves, a quarkonium bound state is produced. A non-perturbative approach needs to be considered, when the relative velocity of the quarks pair is similar to the quarks pair mass³. For the quarkonium case, non-relativistic QCD approaches, including colour-singlet and colour-octet fragmentation processes were found to improve the agreement between data and calculations, albeit dominated by the still large theoretical uncertainties⁴.

The modification of the production yields in Pb-Pb collisions allow to study how charm quarks interact with the medium and, in particular, how they lose energy while passing through it. This energy loss can occur via elastic scatterings of heavy quarks with other partons of the medium or via inelastic processes that induce gluon radiation. Theoretical calculations show that this energy loss depends on the colour charge and the mass of the parton that traverses the medium. Gluons should lose more energy than light quarks due to their larger Casimir factor^{5,6}. Heavy quarks are expected to lose less energy than light quarks due to their larger mass that reduces the probability of gluon emission^{7,8}. Quarkonia, instead, can escape from the medium only if their binding energy is larger than the colour screening potential generated by the deconfined medium⁹. Excited quarkonia states are more likely to melt in the medium, because their binding energy is smaller with respect to their correspondent ground states. Due to the large number of $c\bar{c}$ pairs produced in the collisions at LHC energies, quarkonia states could also be “regenerated” from $c\bar{c}$ quarks produced in different hard scatterings¹⁰. Cold Nuclear

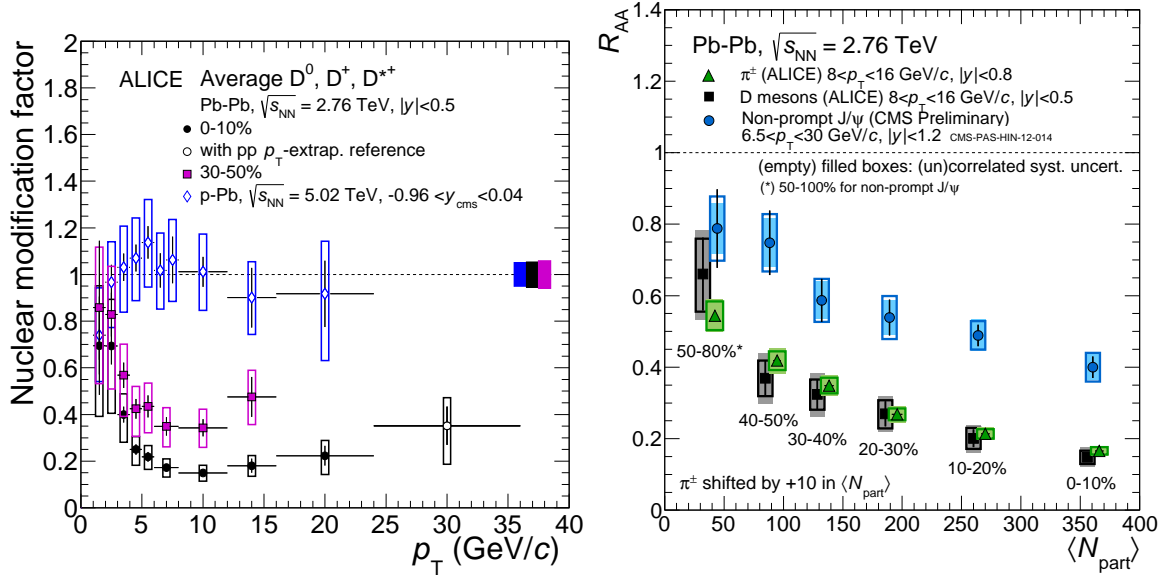


Figure 1 – Left: Prompt D-meson R_{AA} (average of D^0 , D^+ and D^{*+}) as a function of p_T in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the 0–10% and 30–50% centrality classes¹⁵. Prompt D-meson nuclear modification factor R_{pPb} (average of D^0 , D^+ and D^{*+}) as a function of p_T in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV¹⁶. Right: Comparison of the average D-meson R_{AA} in $8 < p_T < 16$ GeV/c with charged pions in the same p_T range¹⁷ and J/ψ from B decays in $6.5 < p_T < 30$ GeV/c.

Matter (CNM) effects, as modification of the Parton Distribution Functions in the nuclei¹¹, gluon radiation¹² or comover interactions¹³ can modify the heavy-quark production. These effects can be studied via p–Pb collisions that were first delivered by the LHC in 2013.

Open heavy-flavour particles produced at mid-rapidity ($|\eta| < 0.9$) are measured in ALICE¹ by the full reconstruction of D-meson decay topologies with displaced vertices and by measuring the spectra of electrons from open heavy-flavour hadron decays. At forward rapidity ($-4 < \eta < -2.5$), their production is studied via muons coming from open heavy-flavour hadron decays. Quarkonia production is measured at mid (forward) rapidity via the di-electron (muon) decay channel; for both cases quarkonia are reconstructed down to transverse momentum $p_T=0$.

Results will be presented in terms of the nuclear modification factor R_{AA} (R_{pPb}): the ratio of the spectra measured in Pb–Pb (p–Pb) collisions, scaled by the number of binary nucleon–nucleon collisions, divided by the one measured in pp collisions, as a function of transverse momentum (p_T) or rapidity (y).

2 Open heavy-flavour results

In order to study the interaction of charm quarks with the medium, the D-meson nuclear modification factor in Pb–Pb collisions has been measured by ALICE as a function of transverse momentum as reported in Fig. 1, left, for two centrality classes (0–10% and 30–50%)¹⁵. A suppression of about a factor 5–6 at $p_T \sim 10$ GeV/c is observed for the most central collisions. For the centrality class 30–50% the suppression is reduced to a factor about 3 in a similar momentum range. In the same figure also the D-meson R_{pPb} is shown and it is compatible with unity¹⁶. This result confirms that the suppression observed in Pb–Pb collisions comes from an interaction of partons with the hot and dense nuclear medium. ALICE measured also the R_{pPb} of leptons from open heavy-flavour decays and no difference from unity was found at backward, central and forward rapidity. Models that include Cold Nuclear Matter effects are in good agreement with the measurements¹⁴.

The D-meson R_{AA} was also been studied by ALICE as a function of the centrality of the

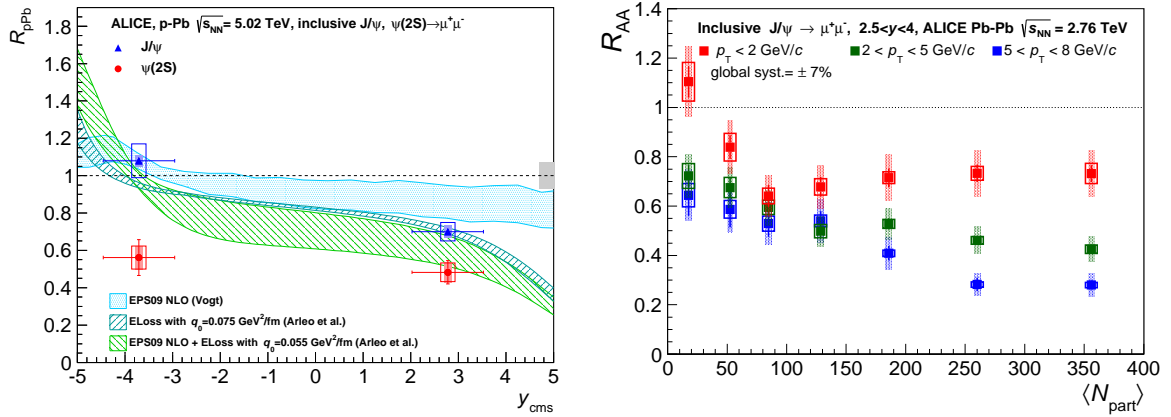


Figure 2 – Left: J/ψ and $\psi(2S)$ R_{pPb} as a function of rapidity integrated over p_T ²¹. Right J/ψ nuclear modification factor measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of centrality for three transverse momentum intervals²³.

collisions: a larger suppression is observed for central collisions than for peripheral ones. For the momentum range $8 < p_T < 16$ GeV/c (Fig. 1, right)¹⁷, the D-meson results are compared to non-prompt J/ψ , coming from B-hadron decay, measured by the CMS experiment¹⁸ in an equivalent kinematic range and to charged pions measured by ALICE. A larger suppression is observed for D mesons than for non-prompt J/ψ while it is similar for π^\pm and D mesons. Theoretical calculations that include a dependence on parton mass and colour charge of the energy loss, can reproduce the results¹⁷.

The study of the D_s^+ -meson production in Pb–Pb collisions is sensitive to the strangeness enhancement observed in heavy-ion collisions. ALICE performed this measurement for the first time in central Pb–Pb collisions¹⁹. The results for strange and non-strange D mesons are compatible within uncertainties and no conclusions can be drawn from the current Run1 data.

3 Quarkonia results

ALICE measured the R_{pPb} of J/ψ in three different rapidity regions: a suppression is observed in the central and forward region, differently to what is measured at backward rapidity where no suppression is reported²⁰. The results are presented as a function of rapidity in Fig. 2, left, integrated over p_T ²¹. The results show a good agreement with models that include shadowing, coherent energy loss or Colour Glass Condensate calculations²⁰.

The measurement of the R_{pPb} of the excited state $\psi(2S)$ has also been performed by ALICE²¹. Results are presented in Fig. 2, left. A similar suppression has been observed at backward and forward rapidity, differently from what is observed for the J/ψ and to what it would be expected, considering the similar initial-state effects for the two charmonium states. Models that include shadowing or coherent energy loss cannot describe the suppression observed at backward rapidity. ALICE performed also more differential studies on the $\psi(2S)$ suppression and no significant p_T dependence is observed²¹. A larger difference between the two states, instead, is observed for central events, in the backward region²². In the forward region, J/ψ and $\psi(2S)$ show very similar patterns as a function of the multiplicity of the collision. Models that include break up of the resonance due to comovers or hadron gas in the final state reproduce the observed trend²².

The R_{AA} of J/ψ at forward rapidity in Pb–Pb collisions is shown as a function of centrality for three different momentum intervals in Fig. 2, right²³. J/ψ with $p_T > 2$ GeV/c show a larger suppression in central collisions than in the peripheral ones. Low- p_T J/ψ , instead, show flatter trend as a function of centrality. The CNM effects inferred from the J/ψ suppression in p–Pb

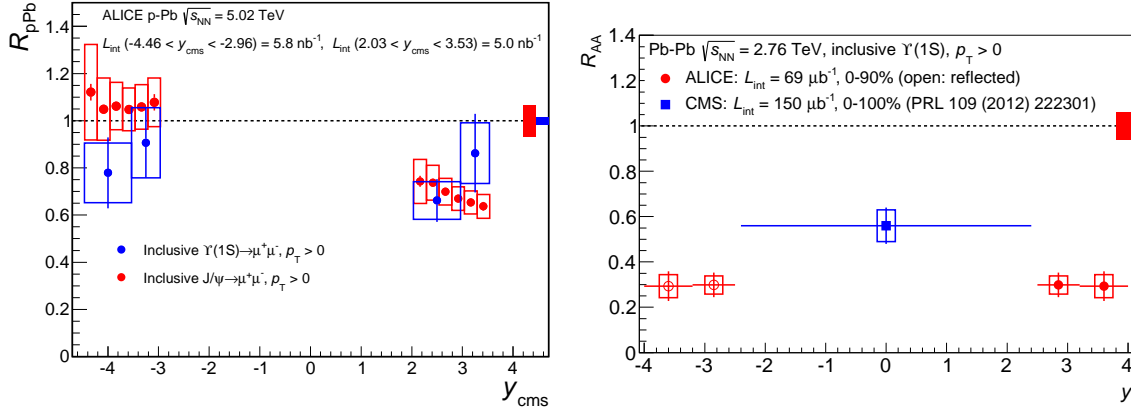


Figure 3 – Left: $\Upsilon(1S)$ R_{pPb} as a function of rapidity integrated over p_T ²⁴. Right: $\Upsilon(1S)$ nuclear modification factor measured by ALICE at forward rapidity²⁶ compared with CMS $\Upsilon(1S)$ R_{AA} at central rapidity.²⁵

collisions at the forward rapidity region are not enough to explain the suppression observed in Pb–Pb collisions. These results are, indeed, in agreement with models that include melting of the J/ψ in the medium due to the colour screening and J/ψ regeneration²³.

ALICE also published the results of the $\Upsilon(1S)$ R_{pPb} , showing a similar value as the J/ψ , in the forward and backward rapidity regions, within uncertainties²⁴ (Fig. 3, left). The results are in agreement with theoretical calculations, though their current large uncertainties. In Pb–Pb collisions, instead, a strong suppression of $\Upsilon(1S)$ state is observed, as shown in Fig. 3, right. Comparing the ALICE and CMS results²⁵, the suppression appears to be larger at forward than at central rapidities²⁶.

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